# NEUTRINO-INDUCED HAZARD - 1

Neutrinos from muon decay may cause significant radiation problems at large distances from the muon colliders and storage rings. Dose at a given location grows with muon energy roughly as $E^3$ due to the increase with energy of the neutrino cross section, of total energy deposited, and of the collimation of the decay neutrinos—each responsible for a factor of $E$. From simple geometry, dose is expected to decline with radial distance as $R^{-2}$ and for a 2+2 TeV collider the Fermilab off-site annual dose limit of 10 mrem is reached only after some 34 km. Our detailed Monte Carlo calculations (1997-1999) confirm the great importance of this problem for high-energy muon colliders. In these studies a weighted neutrino interaction generator is developed and incorporated in the MARS code.

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# NEUTRINO INTERACTIONS VIA MARS

The model represents energy and angle of the particles—$e^{\pm}$, $\mu^{\pm}$, and hadrons—emanating from a simulated interaction. These particles, and the showers initiated by them, are then further processed by the MARS transport algorithms in the usual way. The four types of neutrinos are distinguished throughout: $\nu_\mu$, $\overline{\nu}_\mu$, $\nu_e$, $\overline{\nu}_e$. The model identifies the following types of neutrino interactions for $\nu_\mu$ ($\overline{\nu}_\mu$) and similarly for $\nu_e$, ($\overline{\nu}_e$):

$$\nu_\mu N \rightarrow \mu^+ X, \nu_\mu N \rightarrow \nu_\mu X, \nu_\mu p \rightarrow \mu^+ n, \nu_\mu p \rightarrow \nu_\mu p, \nu_\mu n \rightarrow \nu_\mu n,$$
$$\nu_\mu e^- \rightarrow \nu_\mu e^-, \nu_\mu e^- \rightarrow \nu_e \mu^-, \nu_\mu A \rightarrow \nu_\mu A.$$

Total and differential cross sections for all these processes are taken from the literature. The corresponding sampling algorithms are developed and implemented into the MARS code. For example, for the first reaction—corresponding to charged current deep inelastic neutrino interactions—total cross sections are assumed to be

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$6.7 \times 10^{-39} E_\nu$ cm$^2$ per nucleon ($E_\nu$ in GeV) for neutrinos and half of that for antineutrinos. The differential cross section is taken as

$$\frac{d\sigma}{dx\,dy} = \frac{G^2 xs}{2\pi}\left(Q(x) + (1-y)^2\,\overline{Q}(x)\right) \qquad (1)$$

where $x = -q^2/2M\nu$ with $q$ the momentum transfer, $M$ the nucleon mass, and $\nu$ the energy loss of the neutrino in the lab, $y = \nu/E_\nu$, $G$ is the Fermi coupling constant, $s$ is the total energy in the center of mass, and $Q(x)$, $\overline{Q}(x)$ represent the quark, antiquark momentum distributions inside the nucleon. Both $xQ(x)$ and $x\overline{Q}(x)$ are taken from experiment in numerical form. For antineutrinos the roles of $Q(x)$, $\overline{Q}(x)$ in Eq. 1 are interchanged. Once the direction and momentum of the lepton is decided in the Monte Carlo, its center-of-mass momentum is balanced by a single pion which is then forced to undergo a deep inelastic interaction in the target nucleus. The latter approximates particle production associated with deep inelastic neutrino events.
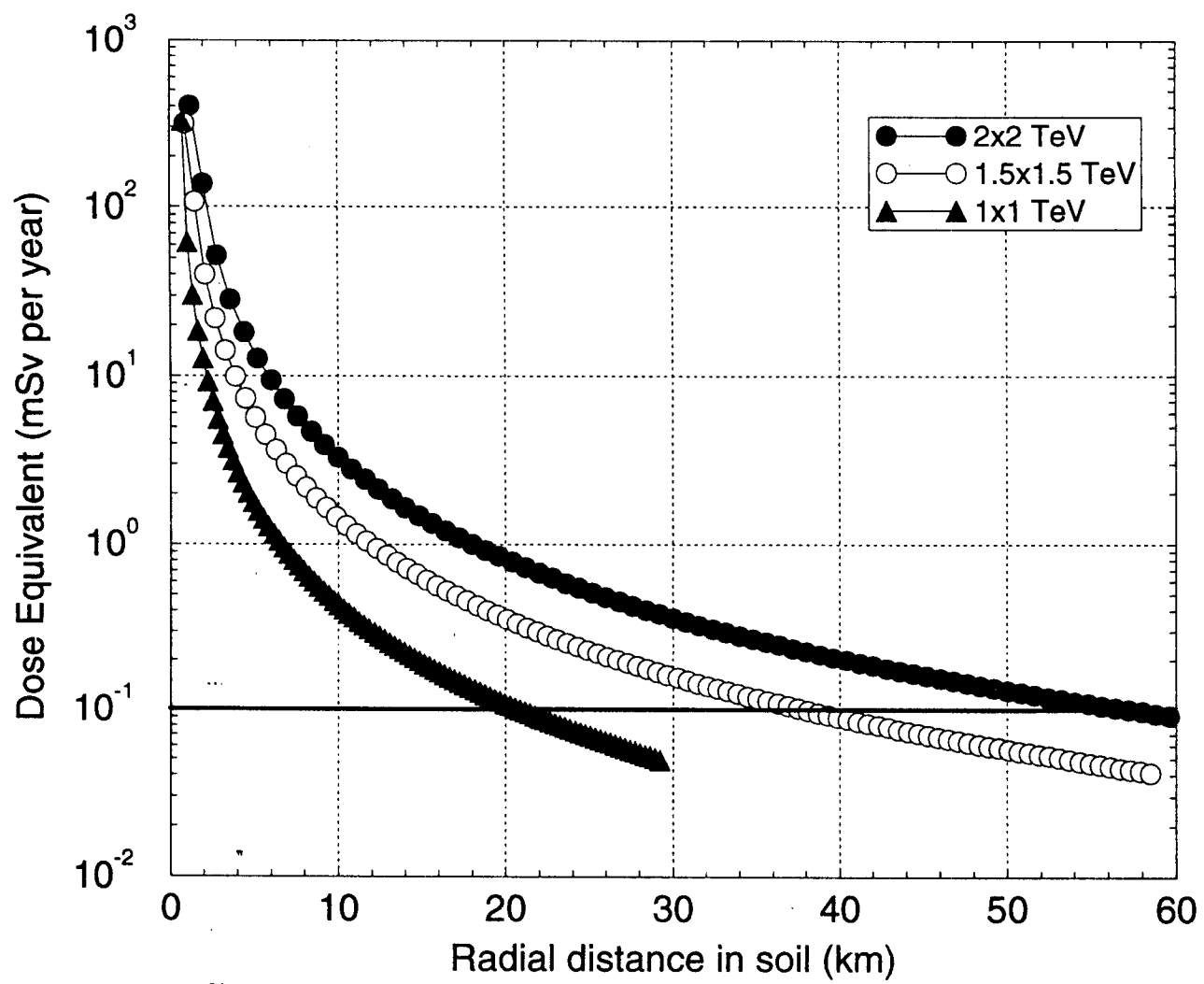
# MUON COLLIDER ARCS

The magnet and beam parameters for both low– and high–energy muon colliders, assumed embedded into Fermilab type soil, are implemented into MARS. For a strictly planar orbit $\nu$-spreading is exclusively due to the transverse momentum acquired at decay. For 2 TeV muons, the fraction of $\nu$-energy—or dose—contained within 10 $\mu$rad spreads only over 1 cm after traversing 1 km and dose decreases rather slowly with the radial distance in the orbit plane. The DOE off-site annual dose limit of 100 mrem ($=1$ mSv) and the Fermilab recommended limit of 10 mrem are reached at radial distances shown in Table 1. Assuming a spherical earth, this radial distance tells us how deep below ground the collider must be placed by equating dose limit(s) with surface dose—apart from legal considerations pertaining to dose delivered deep underground. Note that several meters of soil everywhere around the tunnel are needed in all cases to protect against hadrons and muons.

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# MUON COLLIDER SHIELDING

Table 1: Radial distance, $R$, from the ring center with center-of-mass energy, $\sqrt{s}$, and depth, $d$, needed to reduce neutrino-induced dose at surface to DOE (100 mrem) and Fermilab (10 mrem) annual off-site limits at $N_D$ decays/yr.
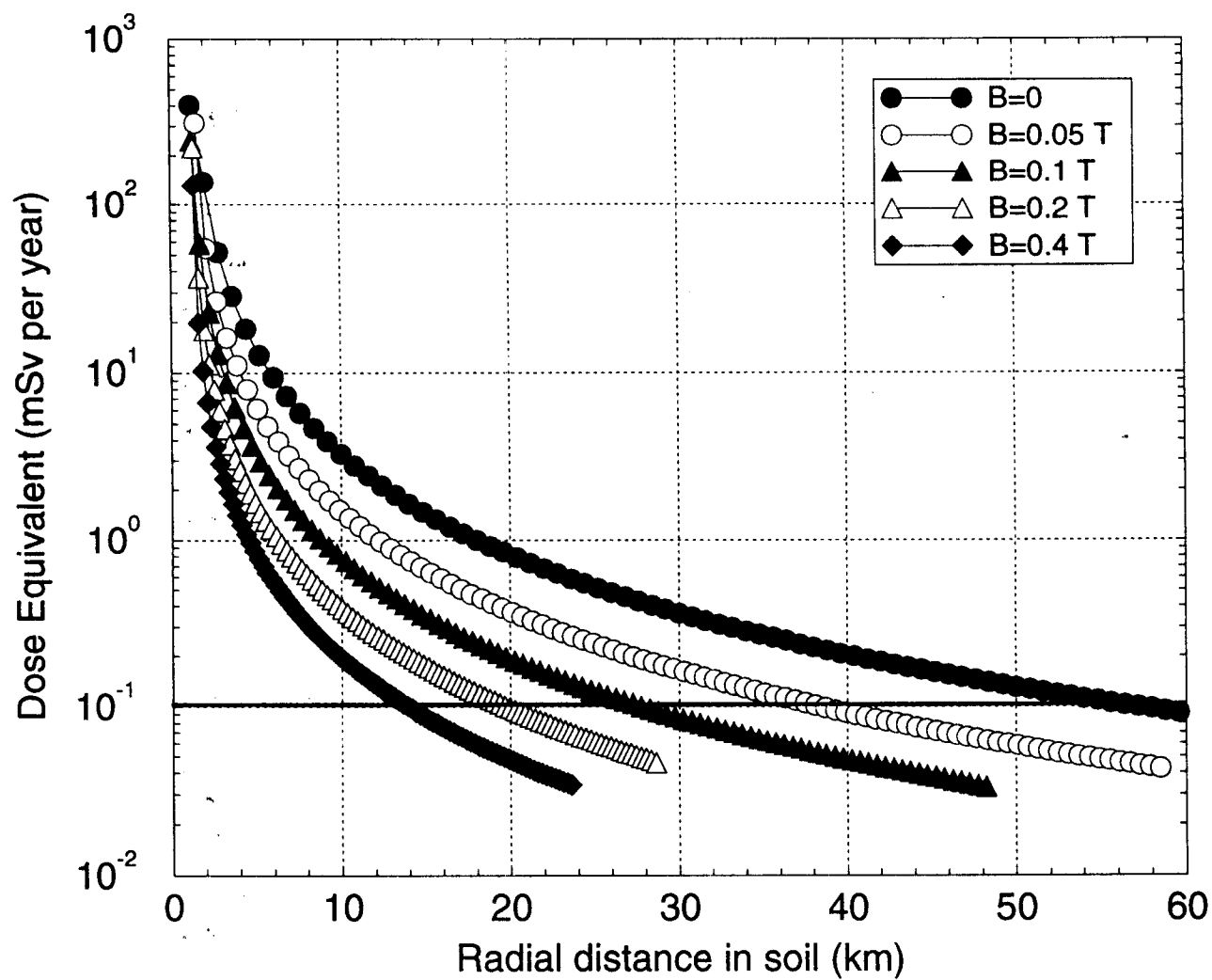
| | | $\sqrt{s}$ (TeV) | 0.5 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|
| | | $N_D \times 10^{21}$ | 0.2 | 0.2 | 2 | 2 | 2 |
| 100 mrem | $R$ (km) | | 0.4 | 1.1 | 6.5 | 12 | 18 |
| | $d$ (m) | | $\leq 1$ | $\leq 1$ | 3.3 | 11 | 25 |
| 10 mrem | $R$ (km) | | 1.2 | 3.2 | 21 | 37 | 57 |
| | $d$ (m) | | $\leq 1$ | $\leq 1$ | 34 | 107 | 254 |

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Dose Equivalent (mSv per year) vs Radial distance in soil (km)
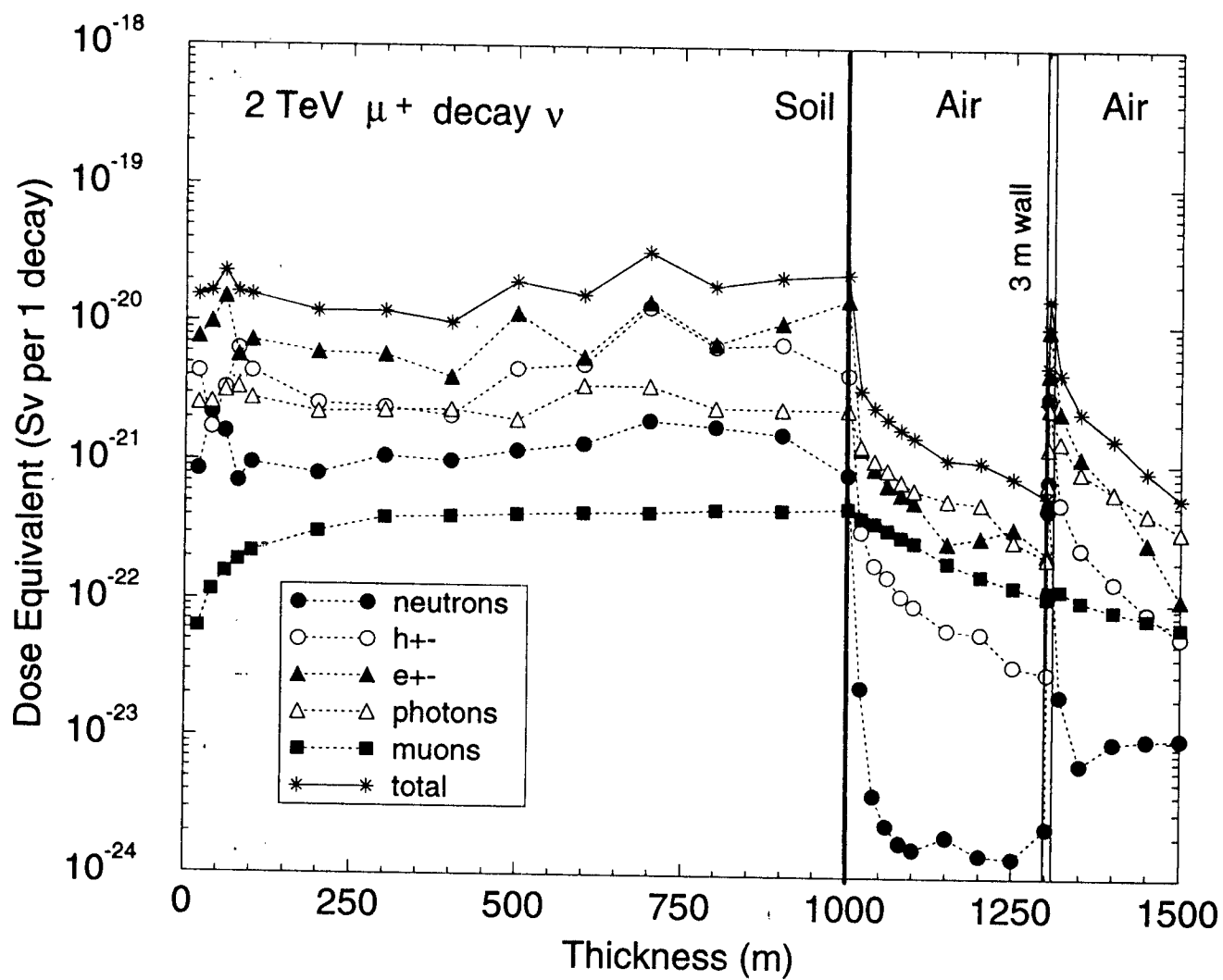
Legend:
- ● 2x2 TeV
- ○ 1.5x1.5 TeV
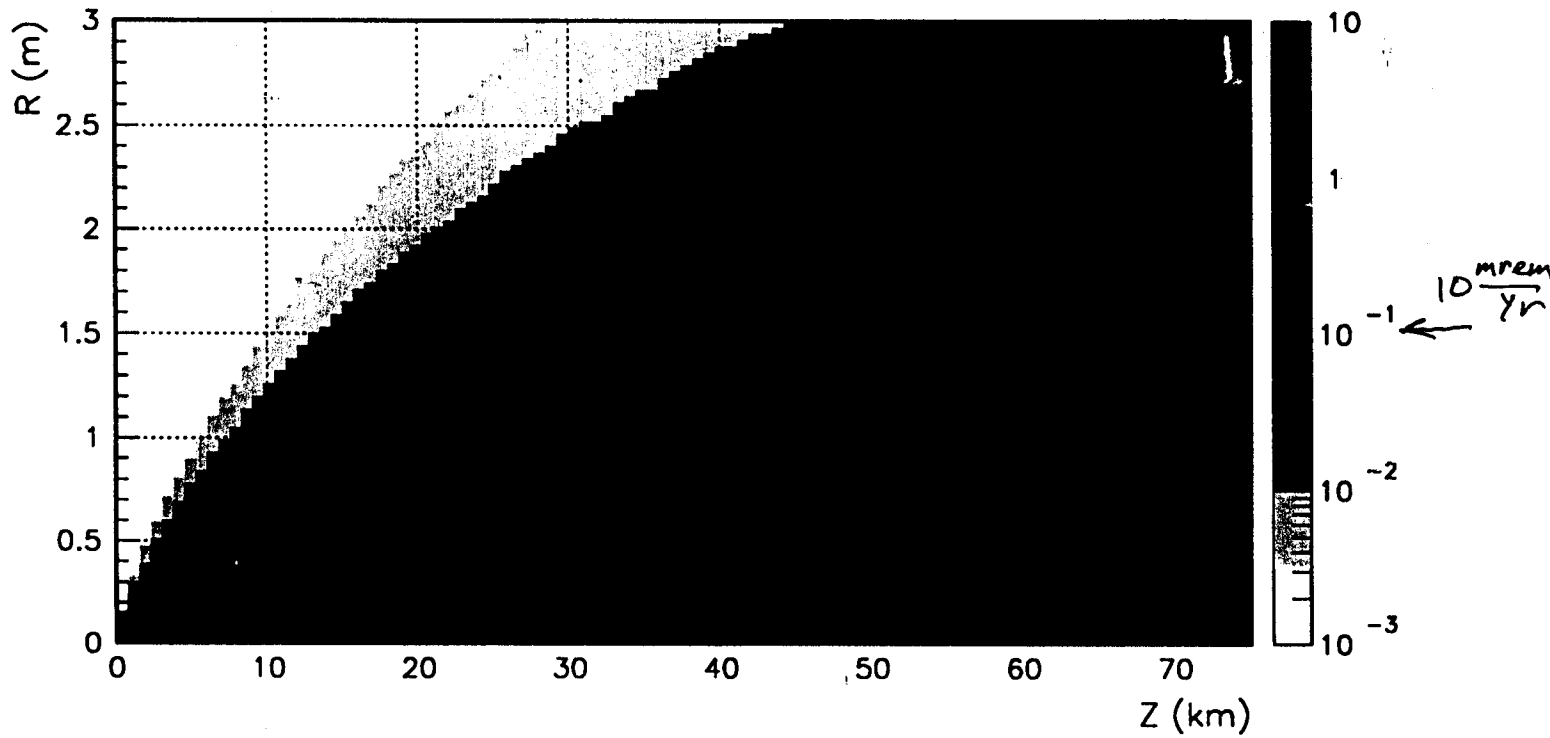- ▲ 1x1 TeV

# MITIGATION VIA BEAM WOBBLING

Since the $\nu$-beam is highly collimated and directional we proposed to vary the direction in which the secondary $\nu$-beam is produced. The beam is already spread in a horizontal disc by the collider dipoles. A vertical wave can be introduced to distribute the radiation over a larger area with lower average dose. This vertical wave should vary in strength and phase over time so as to best dilute the dose. MARS calculations confirm high efficiency of this measure. in the arcs can reduce the $\nu$-flux by more than an order of magnitude. The arc dipoles can be rolled by 20 mrad to achieve the desired 200 $\mu$rad kick (B~0.2 T). To avoid the complication of skewed quadrupoles, net rolls or horizontal magnetic fields are canceled before entering quadrupoles. That is, the first dipole in a set of three is rolled 10 mrad horizontally, the next double that in the opposite direction, and the last by the same amount in the original direction to almost exactly cancel coupling, vertical dispersion, and amplitude effects. Reverse rolls and other changes can be executed from time to time to reduce dose levels in all directions.
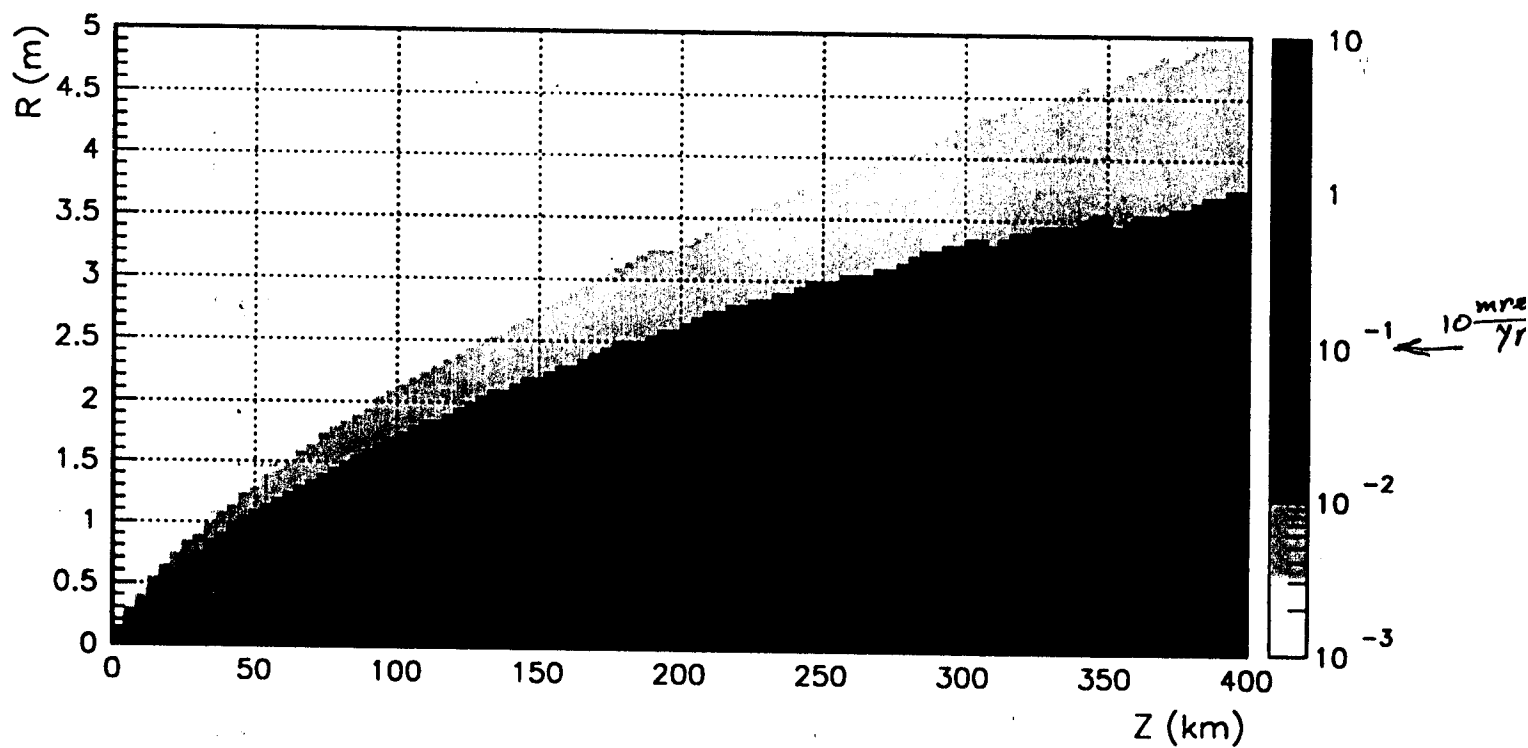
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$2 \times 2\, TeV$

Figure showing Dose Equivalent (Sv per 1 decay) versus Thickness (m) for 2 TeV μ+ decay ν. Regions labeled Soil, Air, and Air with a 3 m wall. Legend: neutrons, h+-, e+-, photons, muons, total.

50 cm drift in 1.5 x 1.5 TeV mumu collider. Equilibrium dose (mSv/yr)

10 cm drift in 10 x 10 TeV mumu collider. Equilibrium dose (mSv/yr)